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Head Injury Potential and the Effectiveness of Headgear in Women's Lacrosse

KATHLEEN ALLEN RODOWICZ,[1] JOSEPH E. OLBERDING,[1] and ANDREW C. RAU[2]

[1]Exponent, Biomechanics Practice, 3440 Market Street Suite 600, Philadelphia, PA 19104, USA; and [2]Exponent, Biomedical Engineering Practice, 3440 Market Street, Suite 600, Philadelphia, PA 19104, USA

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Abstract—Over the past 10 years, lacrosse has grown increasingly popular, making it one of the fastest growing team sports in the country. Similar to other sporting activities, head injuries in lacrosse can and do occur, and the number of lacrosse-related head injuries has increased in recent years. In women's lacrosse, protective headgear is not required, but U.S. Lacrosse and the American Society for Testing and Materials are currently working to develop a headgear standard for the women's game. In the interim, some female lacrosse programs and individual players are wearing soft headgear during play. The effectiveness of this headgear is unknown. Testing was conducted to better understand the material properties of various types of headgear that may be used in lacrosse and the effect of this headgear on head impact response and head injury potential. For the evaluation of head impact response, an instrumented Hybrid III anthropomorphic test device (ATD) was impacted on the side of the head with lacrosse balls and the front and side of the head with a lacrosse stick. The linear and rotational impact response of the head and corresponding acceleration-based injury metrics are reported. Testing was then repeated with the ATD wearing different types of headgear. Tested headgear included a men's lacrosse helmet and two brands of commercially-available soft headgear. For the higher velocity ball impacts, there was no statistically-significant difference in the measured linear and rotational response of the head for the no headgear and soft headgear test conditions. For the lower velocity ball impacts, there was a small, yet statistically-significant, reduction in head linear acceleration for one of the soft headgears tested in comparison to the no headgear test condition, but there was not a statistically-significant difference in the rotational impact response with this headgear. These results indicate that the soft headgear would not be effective in reducing head injury potential during higher velocity ball impacts, such as ball speeds associated with shooting in women's lacrosse. The men's lacrosse helmet reduced both the linear and rotational response of the head for the higher and lower velocity ball impacts. Material testing showed that the padding in the hard helmet exhibited larger strain energy than the padding within the soft headgears when tested in compression. These results correlate with the larger reductions in head accelerations during ball impacts by the hard helmet. For the stick impacts, there were no statistically-significant differences in the lateral impact response of the head for the helmeted and soft headgear test conditions in comparison to the no headgear test condition, but there were statistically-significant, albeit small, differences in the frontal impact response of the head. The similar impact responses of the head during the stick impacts with and without headgear can be attributed to the relatively low severity of these impacts and the characteristics of the impactor.

Keywords—Sport-related concussion, Head impact testing, Ball impact testing, Stick impact testing, Headgear standards, Helmet, Soft headgear, Brine, Full90, ForceField, U.S. lacrosse.

Address correspondence to Kathleen Allen Rodowicz, Exponent, Biomechanics Practice, 3440 Market Street Suite 600, Philadelphia, PA 19104, USA. Electronic mail: krodowicz@exponent.com

ABBREVIATIONS

ATD	Anthropomorphic test device
HIC	Head injury criterion
HIT system	Head impact telemetry system
in	Inch
lbf	Pound-force
mJ	Millijoule
mph	Miles per hour
ms	Millisecond
NCAA	National Collegiate Athletic Association
NEISS	National electronic injury surveillance system
NOCSAE	National Operating Committee on Standards for Athletic Equipment

NSGA	National Sporting Goods Association
oz	Ounce
SI	Severity index

INTRODUCTION

Over the past 10 years, lacrosse has grown increasingly popular among male and female athletes of all levels.[27] In men's lacrosse, body contact is permitted, although intentional head/neck contact is prohibited, and field players wear full-faced helmets, mouth guards, shoulder pads, and gloves for protection.[17,29] In the women's game, intentional body contact and head contact of any kind are illegal, and field players wear eyewear and mouthpieces for protection.[16,28]

Although intentional contact in women's lacrosse is prohibited, incidental head contacts do occur, and concussions and head injuries in the women's game have been reported. According to the 2010 National Electronic Injury Surveillance System (NEISS) injury data and the 2010 National Sporting Goods Association (NSGA) sport participation data, the incidence rate of head injury diagnoses for female lacrosse participants was higher than the incidence rate of head injury diagnoses for female softball, baseball, soccer, basketball, and ice hockey participants.[22] For that analysis, a head injury was defined as an injury to the head that was described as either "concussion" or "internal head injury," and the incidence rate was computed as the number of lacrosse-related head injury diagnoses per days of participation. According to the 2010 NEISS data, head injuries to female participants primarily occurred due to head contact with the lacrosse ball (37%) or stick (41%), with a smaller percentage of injuries occurring due to player-to-player (8%) or ground contact (<1%). In approximately 14% of these NEISS cases, the source of the injurious head contact was unknown. The 2010 NEISS data is consistent with other studies that have reported that the lacrosse ball and stick are the primary sources of head injuries in women's lacrosse.[5]

It has been suggested that women's lacrosse participants should wear a form of protective headgear to reduce the risk of head injury during play.[6,10] U.S. Lacrosse and the American Society for Testing and Materials (ASTM) are currently working to develop a headgear standard for the women's game. In men's lacrosse, a helmet with a hard outer shell is utilized. Helmets have been shown to be effective in reducing linear accelerations of the head during impact, making them effective in reducing the risk of skull fracture and severe brain injuries,[4] injuries that, to the authors' knowledge, have never been reported in the women's game. The most common head injury in high school and collegiate women's lacrosse is concussion.[11] The effectiveness of a helmet on reducing the rotational impact response of the head, and thereby rotational injuries, such as concussion, needs to be further explored.[4] Currently, the men's lacrosse helmet, or any other hard helmet, is illegal in the women's game.[16,28] Not only is the effectiveness of the helmet in preventing concussions unknown, but hard helmets have been identified in certain instances as causing injury to opposing players during player-to-player contacts.[21] Additionally, it has been proposed that the use of protective equipment, such as a helmet, may encourage illegal and injurious behaviors in certain sports.[14]

While currently there is no standardized headgear in women's lacrosse, some organizations are moving toward requiring female lacrosse participants to wear some form of soft headgear during play.[6,10] According to current women's lacrosse rules, soft headgear, consisting of a "foam-type material," may be worn.[16,28] Although some studies do suggest that certain soft headgear may provide some benefit during higher energy impacts in sports such as soccer,[15,30] the effectiveness of soft headgear in preventing or reducing the severity of head injuries in women's lacrosse is unknown. To better understand the magnitude of head impacts in women's lacrosse and the risk of head injury to participants, testing was conducted to measure the head impact response during simulated women's lacrosse ball and stick impacts and to evaluate the effectiveness of different types of headgear on head and concussion injury potential. Material testing of the headgear was also conducted to determine if the effectiveness of the headgear correlated with the strain energy capacity of the headgear.

METHODS

Ball and Stick Impact Testing

A Hybrid III 50th-percentile male anthropomorphic test device (ATD) was utilized to evaluate the response of the head during simulated women's lacrosse ball and stick impacts. The head of the ATD (1846-D head, Denton ATD, Milan, Ohio) was instrumented with a 9-accelerometer array in a 3-2-2-2 configuration (7264-2000, Endevco, San Juan Capistrano, CA). Channel orientations were in accordance with the SAE J211 dummy head coordinate system with the positive x-axis forward, the positive y-axis to the right, and the positive z-axis downward (SAE, 1995).The ATD was seated in a chair that was fixed to the floor, and the

torso of the ATD was constrained in the chair to prevent movement of the torso and body of the ATD during the head impact.

The Full90 Performance Premier Headgear (Full90 Sports Inc.; San Diego, CA), ForceField FF Protective Sweatband (ForceField FF (NA), Ltd.; Great Neck, NY), and Brine Men's Lacrosse Helmet (Warrior Sports; Warren, MI) products were considered in this study. The headgear was placed onto the head of the ATD in accordance to the manufacturer's instructions. A ''no headgear'' condition was also tested to better understand the baseline head impact response associated with women's lacrosse head impacts and also to serve as a control during the statistical analysis of the data. Photographs of each test condition are shown (Fig. 1). Prior to testing, protective eyewear (STX 4Sight Plus Women's Adult Lacrosse Goggle; Baltimore, MD) was positioned on the ATD head with the ForceField headband and the Full90 headgear to ensure the headgear were compatible with this type of eyewear.

Lacrosse balls were used to simulate women's lacrosse ball impacts (deBeer Lacrosse; St. Louis, MO). The balls met the National Collegiate Athletic Association (NCAA) and National Federation of State High School Associations (NFHS) specifications, per labeling. The balls were evaluated for mass, circumference, and compression force, parameters considered in the proposed NOCSAE standard ND 049-05m12a.[18] The balls had an average circumference of 7.8 $\pm$ 0.0 in., an average mass of 5.3 $\pm$ 0.1 oz, and an average peak force to compress the balls by 25% of their original diameter of 228 $\pm$ 21 lbs. The balls were projected into the head of the ATD using a JUGS Jr. Pitching Machine (JUGS Sports, Tualatin, OR). The pitching machine exit chute was positioned several feet from the side of the ATD head. A pitcher's protective L-screen was placed between the pitching machine and the ATD to protect the feeder from rebound of the ball after head impact. The entire test setup was enclosed within a batting cage (Fig. 2). Machine-indicated ball velocities of approximately 30 and 60 miles per hour were chosen to simulate women's passing and shooting speeds, respectively.[3,12] Prior to testing, a radar gun was used to verify that ball speeds were within 7% of the target speeds. Three replicate ball impacts at each of these speeds were performed for the three headgear conditions and in the no headgear condition. Ball impacts were targeted to the side of the head at approximately the center of gravity (CG). If an impact resulted in gross movement of the headgear, the headgear was repositioned after impact. New headgear was substituted after each set of three ball impacts.

To simulate lacrosse stick impacts, each headgear condition and the no headgear condition was subjected to five strikes to the front and side of the ATD head using a lacrosse stick (Brine 6065 shaft and Amonte head; Warrior Sports; Warren, MI) swung by a female experimenter. The impacts were meant to simulate a stick check, where the side of the stick is used to knock the ball out of another player's cross. For these impacts, the swing distance was relatively short (less than approximately 2 feet) and the impacts were delivered in rapid succession. The impacts were not intended to simulate the maximum swing speed of a player, but rather to simulate a situation where one player is attempting to knock the ball from the pocket of an opposing player's stick. The target impact location on the stick was the plastic region of the head, near the bottom of the basket. The side of the cross was used for these impacts. New headgear was substituted after each series of frontal and lateral stick impacts.

Data were acquired at a rate of 10 kHz and raw data were filtered using channel frequency class (CFC) 1000. The tri-axial linear accelerations at the CG of the head were measured for each of the impacts and the resultant linear accelerations (g) were determined. The rotational accelerations and velocities were obtained by transformation of off-axis linear accelerometer data according to the method of Padgaonkar *et al.*[19]

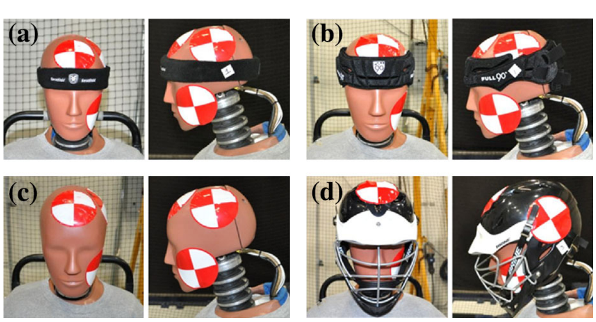

FIGURE 1. Front and side views of each test condition (a) ForceField, (b) Full90, (c) no headgear, and (d) helmet.

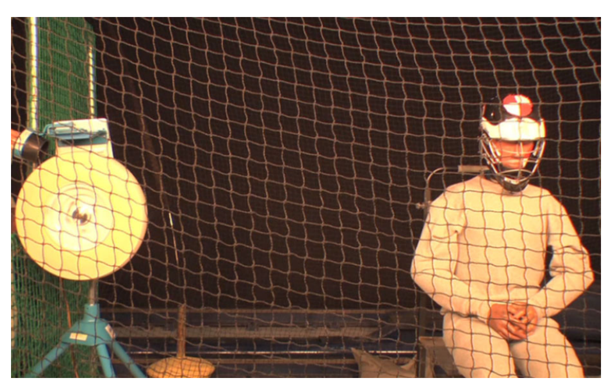

FIGURE 2. Photograph of test setup. Lateral restraints restricted lateral movement of the ATD during the lateral impacts, and the back rest of the chair restricted the rearward motion of the ATD during the frontal stick impacts.

The Head Injury Criterion (HIC) with a maximum 15 ms window and the Severity Index (SI) were calculated from CG resultant linear accelerations, in g. The SI is defined as:

$$\mathrm{SI} = \int_0^T a^{2.5}\,dt,$$

where T is the test period and a is the resultant linear acceleration.

The HIC is defined as:

$$\mathrm{HIC} = (t_2 - t_1)\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a\,dt\right]^{2.5}$$

where a is the resultant linear acceleration and the values t_1 and t_2 are the time points for which the HIC is maximized. The interval $(t_2 - t_1)$ that the HIC was calculated was limited to a maximum of 15 ms. Real-time (30 frames per second) and high-speed video (500 frames per second) were captured for the ball and stick impacts. In order to assess the accuracy of the ball and stick impacts, two authors independently reviewed all impacts.

Material Testing

The padding within the tested headgear was tested in compression in order to evaluate the mechanical responses of the padding and compare the amount of energy required to deform the tested materials. For each headgear, a specimen of the material from the thickest section was extracted in order to preserve the full cross section. For the lacrosse helmet, the hard exterior shell was removed and only the interior foam was tested. The thickness of each test specimen was first measured using digital calipers (Mitutoyo; Aurora, IL); then the specimen was placed on a flat, stainless steel compression platen and a flat, circular indenter with an outer diameter of 1.0 in was used to compress the specimen at a rate of 0.5 in/min. Each specimen was compressed to 50% of its original thickness. Load and displacement data were acquired at a rate of 50 Hz during testing, and the energy required to deform the material by 25 and 50% of its original thickness was calculated as the area under the force–displacement curve.

Statistical Analysis

The average response and standard deviation were determined for each ball and stick test condition. A one-way analysis of variance (ANOVA) was utilized to assess differences in the response of the head between the headgear and no headgear test conditions. Using the no headgear condition as control, Dunnett's multiple comparisons tests were used to determine if differences between each headgear and the no headgear condition were significant, with $p < 0.05$ considered significant.

RESULTS

Ball Impacts

At both ball velocities, the helmeted test condition resulted in statistically-significant reductions in each of the impact parameters considered, including the average peak linear acceleration, average peak rotational acceleration, average peak rotational velocity, average HIC, and average SI in comparison to the no headgear test condition. The use of the helmet reduced each of these impact responses by at least 50%, with the greatest reductions seen in average HIC and SI, which were between 84 and 93%. For these data comparisons, the associated p-values were less than 0.001. Reductions were seen for both the 30 and 60 mph ball impacts.

For the ball impacts at approximately 30 mph, there was no difference in the average peak linear acceleration, average peak rotational acceleration, or average peak rotational velocity of the head between the ForceField test condition and the no headgear test condition. Similarly, there was no difference between the average peak rotational acceleration and average peak rotational velocity of the head between the Full90 and no headgear test conditions. However, there was a small, yet statistically-significant, reduction in the average peak linear acceleration of the head between the Full90 and no headgear test conditions. The reduction in the average peak linear acceleration associated with the Full90 headgear was approximately 12%, with a corresponding p value of 0.044. For the ball impacts at approximately 30 mph, there was a statistically-significant reduction in HIC and SI for the ForceField and Full90 test conditions with respect to the no headgear test condition. These reductions ranged from 20 to 28%, with corresponding p-values ranging from 0.007 to 0.043. It should be noted that the ForceField headgear did not contain padding at the side of the headband (impacted region).

The ball impacts at an impact speed of approximately 60 mph resulted in a larger impact response of the head than the ball impacts at speeds of approximately 30 mph. For the ball impacts at approximately 60 mph, the statistical analysis demonstrated that there were no significant differences between the average peak linear acceleration, average peak rotational acceleration, or average peak rotational velocity of the

TABLE 1. Average peak resultant head accelerations and velocity and HIC and SI values, ±SD, for the approximately 30 mph and 60 mph ball impacts.

	ForceField		Full90		Helmet		No headgear
Head linear acceleration (g)							
30 mph	44.2 ± 0.4	*0.121*	42.8 ± 3.5*	*0.044*	10.6 ± 2.5*	*< 0.001*	48.9 ± 2.4
60 mph	105.0 ± 1.9	*0.298*	105.0 ± 2.0	*0.292*	52.9 ± 3.4*	*< 0.001*	108.7 ± 3.2
Head rotational acceleration (rad/s^2)							
30 mph	7014.5 ± 181.1	*0.900*	6804.8 ± 52.2	*0.990*	1411.4 ± 391.4*	*< 0.001*	6827.9 ± 706.0
60 mph	19353.3 ± 988.9	*0.157*	19971.9 ± 1274.4	*0.426*	7732.6 ± 898.8*	*< 0.001*	21123.4 ± 906.9
Head rotational velocity (rad/s)							
30 mph	9.07 ± 0.31	*0.459*	8.96 ± 0.40	0.668	4.06 ± 0.15*	*< 0.001*	8.57 ± 0.79
60 mph	20.46 ± 0.98	*0.160*	21.49 ± 1.89	0.637	9.07 ± 0.32*	*< 0.001*	22.48 ± 0.86
HIC							
30 mph	13.6 ± 0.3*	*0.043*	12.1 ± 2.0*	*0.007*	1.2 ± 0.4*	*< 0.001*	16.9 ± 1.8
60 mph	97.5 ± 3.8	*0.184*	93.9 ± 5.4*	*0.044*	15.2 ± 1.1*	*< 0.001*	104.8 ± 6.1
SI							
30 mph	15.9 ± 0.3*	*0.040*	14.4 ± 2.4*	*0.008*	1.9 ± 0.4*	*< 0.001*	19.9 ± 2.1
60 mph	112.3 ± 4.3	*0.226*	108.3 ± 5.8	*0.056*	19.8 ± 1.1*	*< 0.001*	120.0 ± 7.2

Associated *p*-values are in italics (significantly-different comparisons indicated by *).

head between the soft headgear and no headgear test conditions. Additionally, there were no statistically-significant differences in the HIC and SI between the ForceField test condition and the no headgear test condition, and there was no statistically-significant difference in the SI between the Full90 test condition and the no headgear condition. There was a small, although statistically-significant, reduction in HIC for the Full90 test condition in comparison to the no headgear test condition. The reduction in HIC for the Full90 test condition was approximately 10%, with a *p*-value of 0.044, Table 1.

For all ball impacts, the averages and standard deviations (SD) for peak resultant linear acceleration, peak resultant rotational acceleration, peak resultant rotational velocity, HIC, and SI and corresponding *p*-values comparing each headgear condition to the no headgear test condition are reported in Table 1.

Ball impacts to the bare headform (no headgear) and to the headform with the soft headgear were associated with impact durations of approximately 2–4 ms. The helmeted ball impacts were associated with impact durations of approximately 7–15 ms. Examples of the lateral head accelerations associated with the ball impacts for each of the headgear test conditions and the no headgear test condition are shown (Fig. 3).

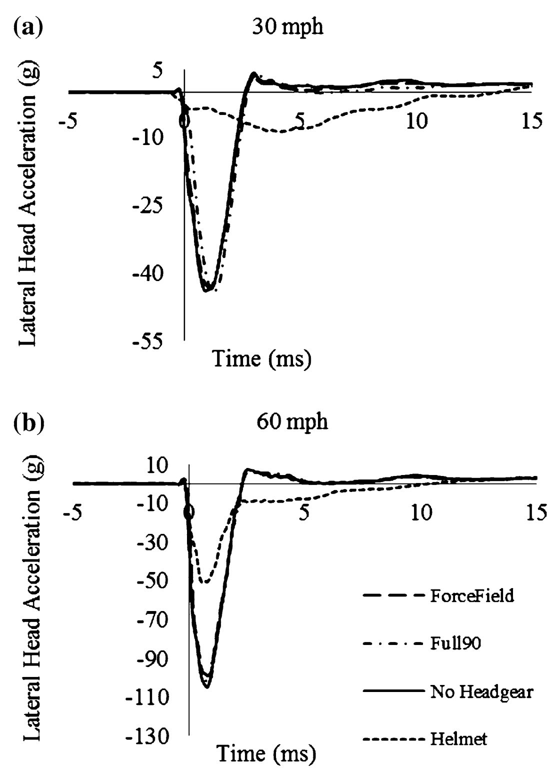

FIGURE 3. Impact durations for the 30 mph and 60 ball impacts for the tested headgear and the no headgear test conditions.

Stick Impacts

Frontal and lateral stick impacts for all headgear test conditions and the no headgear test condition resulted in relatively low head accelerations in comparison to the ball impacts. For the lateral stick impacts, statistically-significant differences between the headgear and the no headgear test conditions were not observed. For the frontal stick impacts, small, however statistically-significant, differences were observed for all headgears with respect to the no headgear test condition in terms of average peak linear and rotational head accelerations. The average peak rotational velocity for the frontal stick impacts with the ForceField headgear was statistically-significantly different than the no headgear condition,

TABLE 2. Average peak resultant head accelerations and velocity and HIC and SI values, ± SD, for the frontal and lateral stick impacts.

	ForceField		Full90		Helmet		No headgear
Head linear acceleration (g)							
Frontal	8.0 ± 1.1*	*0.022*	6.4 ± 1.3*	*< 0.001*	5.1 ± 1.1*	*< 0.001*	10.7 ± 2.0
Lateral	6.5 ± 2.1	*0.067*	5.1 ± 0.8	*0.840*	4.8 ± 1.2	*0.980*	4.6 ± 0.6
Head rotational acceleration (rad/s^2)							
Frontal	533.6 ± 204.2*	*0.002*	447.7 ± 75.3*	*< 0.001*	422.9 ± 37.1*	*< 0.001*	880.7 ± 144.6
Lateral	733.2 ± 235.9	*0.340*	501.4 ± 140.9	*0.780*	409.9 ± 58.0	*0.254*	581.2 ± 178.3
Head rotational velocity (rad/s)							
Frontal	4.8 ± 1.1*	*0.004*	3.2 ± 0.7	*0.909*	2.7 ± 0.2	*0.959*	2.9 ± 0.7
Lateral	3.1 ± 0.5	*1.000*	3.7 ± 1.1	*0.471*	3.0 ± 0.7	*0.992*	3.2 ± 0.8
HIC							
Frontal	0.40 ± 0.12	*0.491*	0.18 ± 0.04*	*0.003*	0.30 ± 0.14	*0.067*	0.50 ± 0.17
Lateral	0.30 ± 0.12	*0.092*	0.22 ± 0.08	*0.525*	0.32 ± 0.19	*0.054*	0.14 ± 0.05
SI							
Frontal	0.65 ± 0.20	*0.932*	0.32 ± 0.09*	*0.012*	0.44 ± 0.16	*0.094*	0.70 ± 0.25
Lateral	0.42 ± 0.17	*0.224*	0.34 ± 0.11	*0.685*	0.48 ± 0.23	*0.108*	0.27 ± 0.07

Associated *p*-values are in italics (significantly-different comparisons indicated by *).

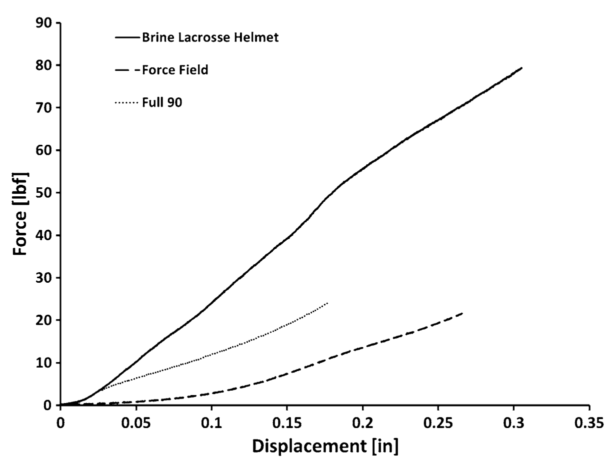

FIGURE 4. Force-displacement plots for all equipment material compression tests. Note: each specimen was compressed to 50% of the original specimen thickness.

but this difference was an increase in the rotational velocity of the head. The averages and standard deviations for peak resultant linear acceleration, peak resultant rotational acceleration, peak resultant rotational velocity, HIC, and SI, and associated *p*-values, for the stick impacts are included in Table 2.

Material Testing Results

Material specimens from the different headgear were tested in compression in order to evaluate the amount of energy required to deform the specimens by 25 and 50% of their original specimen thicknesses. Force–displacement plots of the material compression tests illustrate the material response of each specimen (Fig. 4). The area under the force–displacement plots, i.e., the strain energy, represents the energy required to deform the specimen.[13]

The amount of energy required to deform each specimen by 25 and 50% of its original thickness are provided in Table 3. At both the 25 and 50% compression states, the men's lacrosse helmet exhibited substantially higher strain energies than the other specimens. At 50% compression, the Full90 and ForceField specimens exhibited strain energies that were less than 20% of the strain energy of the men's lacrosse helmet.

DISCUSSION

Testing was conducted to better understand the response of the head during women's lacrosse ball and stick head impacts. Determining head impact response is important to developing a standard for women's lacrosse headgear. The effect of different types of headgear on head impact response was evaluated.

For the ball impacts, the statistical analysis demonstrated that the two types of soft headgear did not substantially affect the measured response of the head in comparison to the no headgear test condition (the Full90 headgear did produce a small, but significant, change in average peak linear head acceleration at 30 mph). These data indicate that the use of the tested soft headgear would not reduce the likelihood of a player sustaining a head injury or concussion during a high velocity ball impact, such as an impact speed associated with women's shooting speeds. Concussion injury is typically associated with the rotational response of the head during an impact. The inability of the soft headgear to reduce the rotational impact

TABLE 3. Strain energy required to deform each material specimen by 25 and 50% of the original specimen thickness.

	Original thickness (in)	Strain energy (mJ)	
		25% Compression	50% Compression
Men's lacrosse helmet	0.61	310	1373
Full90	0.35	54	220
ForceField	0.53	27	228

response of the head may indicate that it would not be effective in reducing the risk of concussion injury during ball impacts at either of the tested impact speeds. Although in some of the ball tests statistically-significant differences in HIC and SI were determined between the soft headgear and no headgear test conditions, the metric from which these values were derived, linear acceleration, was similar for the soft headgear and no headgear test conditions.

The men's lacrosse helmet significantly reduced the average ball impact response of the head in comparison to the no headgear test condition for all three primary kinematic measures under both impact severities. Although the men's helmet is specifically tested and certified based on its linear response during impact, the helmet was effective in reducing both the linear and rotational response of the head during the ball impacts, suggesting that a men's helmet would reduce the risk of head injury during similar impact conditions.

The stick impacts resulted in contact between the plastic region of the head of the stick and the headform of the ATD. Video analysis demonstrated that during these impacts, the plastic of the lacrosse stick deformed, reducing the magnitude of the impact force applied to the head of the ATD. This resulted in a relatively low impact response of the head. The data demonstrated that there was either no statistically-significant difference (in the case of lateral stick impacts) or no substantial difference (in the case of frontal stick impacts) between the response of the head during impacts with headgear in comparison to the no headgear test condition. Had a stiffer structure of the stick been used to impact the headform of the ATD, i.e., the shaft of the stick, it is expected that the accelerations of the head would have been greater and differences between impacts with headgear and without headgear would have been better appreciated. The authors caution that these results do not suggest that a helmet is ineffective in reducing the kinematic response or injury potential of the head during all stick impacts. These results demonstrate that additional testing using different impact locations on the stick and additional test subjects is necessary to better evaluate stick impact responses and headgear effectiveness.

Head impact injury potential is a function of the magnitude of the head acceleration and the duration of the impact. Recent studies have analyzed head injury risk from data collected during collegiate football head impacts *via* the head impact telemetry (HIT) System. The impulse durations associated with the HIT System data ranged from approximately 6–15 ms,[2,23,25] similar to the pulse lengths associated with the helmeted lacrosse ball impacts in this study, which ranged from approximately 7–15 ms. Utilizing the HIT System data, studies have determined that a linear acceleration of 100 g may be associated with less than a 1% risk of concussion.[7,8,23] A later study by Rowson and Duma adjusted the HIT System data to account for underreporting of concussions and concluded that concussive impacts recorded *via* HIT System were associated with an average linear head acceleration of 104 ± 30 g and an average rotational head acceleration of 4726 ± 1931 rad/s.[24] The Rowson and Duma study estimated concussion risk based on combined linear and rotational head accelerations.[24] Given the similarity between the impulse durations in the football studies recorded *via* HIT System, and the helmeted lacrosse ball impacts recorded in this study, it may be appropriate to consider the concussion injury risk curves created using the HIT System data in the context of helmeted lacrosse ball impacts. For the ball impacts to the helmeted ATD, the average peak linear acceleration of the head at an impact speed of approximately 60 mph was approximately 53 g, with an average peak rotational acceleration of 7800 rad/s. Utilizing the risk curve developed by Rowson and Duma,[24] the ball impacts at approximately 60 mph to the helmeted head are associated with approximately an 18% risk of concussion. Using these same curves, the ball impacts at approximately 30 mph are associated with less than a 1% risk of concussion injury.

For the ball impacts with the soft headgear or no headgear, the duration of the impact was approximately 2–4 ms, similar to durations reported in studies which have investigated baseball impacts to the head.[26] The similarity between the impact duration and shape of the acceleration pulses for the soft headgear and no headgear test conditions is a demonstration of the inability of the soft headgear to attenuate the ball

impact energy. Given the shorter impulse duration associated with these impact conditions, concussion injury potential was not evaluated for the soft headgear and no headgear ball impact conditions.

For impact durations of 10–30 ms, concussion injury has been associated with a HIC value of 240–250 and a SI score of 300.[1,20,31] Given the considerably shorter pulse durations associated with the ball impacts for the headgear and no headgear test conditions in this testing, HIC and SI-based concussion injury was not evaluated for these head impacts. The lateral and frontal stick impacts were associated with impulse durations of approximately 15–20 ms. Head accelerations associated with the stick impacts were relatively small and therefore associated with a very low risk of concussion injury according to acceleration, HIC, and SI risk curves.

Preliminary data for ball impacts to the frontal region of the head of the ATD demonstrated that the hard helmet reduced both linear and rotational head impact responses of the head in comparison to the no headgear test condition, but the soft headgear did not substantially influence the impact response. Due to the small sample size of the frontal impacts, a statistical analysis was not performed on these data and therefore these results are not presented.

One of the primary functions of protective headgear is to dissipate force and energy during impact. Energy dissipation and storage by protective headgear is achieved by the plastic and elastic deformation of the construction materials, often a shell and a liner.[9,13] The area under the stress–strain (or, similarly, load–displacement) curve has been used to quantify energy absorption for the comparison and optimization of materials used in protective headgear.[13] Such strain energy metrics can be used to predict and model energy transfer during impact scenarios. While strain energy is not the only contributing parameter that determines protective capability, the protective benefit of the men's lacrosse helmet in contrast to the soft headgear may be explained, in part, by the energy absorbing properties of the headgear. Considering the quantitative strain energy parameters measured and qualitatively inspecting the load–displacement curves, the results of the headgear compression testing demonstrate that the padding within the men's lacrosse helmet has a greater capacity for energy absorption than both of the soft headgear specimens. This is consistent with the head impact test data, which demonstrated larger reductions in head accelerations during the ball impact testing with the hard helmet in comparison to the soft headgear or no headgear test conditions. Although headgear strain energy properties are not the only factors in determining its effectiveness, these data suggest that the higher strain energy response of the men's lacrosse helmet material contributed to the resulting impact responses of the headform.

According to its label, the men's lacrosse helmet utilized in this testing complied with the NOCSAE standard for this headgear, which considers the linear response but not the rotational response of the head during an impact. Ball impact testing conducted with this helmet reduced the linear as well as the rotational response of the head in comparison to the no headgear test condition. Since concussion risk is associated with both linear and rotational impact responses of the head, this suggests that the use of this helmet may reduce the risk of concussion during ball impacts to the head. The soft headgear tested was not certified to any known test standard, and the use of this headgear did not substantially change the impact responses of the head during the ball impacts. Care should be taken when utilizing headgear that was not designed to protect players under specific impact conditions.

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CONFLICT OF INTEREST

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